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Physical principles of losses in thin film solar cells and efficiency enhancement methods

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ABSTRACT

Although there are individual reports on the efficiency enhancement methods in the form of news articles, highlights and research papers in the literature; there is no article mentioning all the methods used for enhancing the efficiency of a thin film solar cell. This article is focused on discussing the physical principles of losses in a thin film solar cell and the methods used for enhancing the efficiency. The article begins with a general outline about the thin film solar cell, its advantages, material requirements and its characteristics. Various losses in solar cell and how to overcome them in order to improve the efficiency of solar cell are discussed. Some novel methods used for enhancing the efficiency of thin solar cell are also discussed. Towards end, summary of some other parameters which can add to the efficiency of solar cell are described.

Contents

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1. Introduction

Earth receives more solar energy in an hour than we consume in an entire year. Covering 0.16% of the earth's surface with 10% efficient cells would provide electricity more than the current total energy demand of the planet. Solar photovoltaic (PV) works on the principle of photoelectric effect. It involves direct conversion of sunlight into electricity. The photovoltaic effect was first discovered by a French physicist A.E. Becquerel in 1839 [1,2]. The first solar power generation was shown by Chapin, Fuller and Pearson of Bell labs in 1954 [3]

1.1. Advantages and limitations of a photovoltaic cell

Solar cell has both advantages and limitations based on their availability, operation and principle. Some of the advantages are; being environmentally friendly, no noise, no moving parts, no emissions, no use of fuels and water, minimal maintenance requirements, long lifetime (up to 30 years), electricity is generated wherever there is light (solar or artificial), PV operates even in cloudy conditions, modular "custom-made" energy can be sized for any application from a watch to a multi-megawatt power plant. Some of the disadvantages are: PV cannot operate without light (no output at night), lower output in unfavourable weather, use of toxic materials in some solar cell, high initial costs that overshadow the low maintenance costs and lack of fuel costs, large area is needed for large scale applications. PV generates direct current and therefore special DC appliances or inverters are needed. For off-grid applications energy storage is needed [4].

1.2. Theory of solar cell

When the energy of an incoming photon is equal to or greater than the band gap of the material, the photon is absorbed by the material and it excites an electron into the conduction band. A hole is left behind and another electron from valence band moves to this position leaving behind a hole. In this way hole moves through the lattice. Thus it can be said that absorbed photon creates electron–hole pair. When p and n type materials are brought together, diffusion of carriers take place and charges build up on either side of junction and create an electric field. The p–n junction formed helps in separating these electron–hole pair. It acts like a semipermeable membrane and allows only one type of carrier to pass through it. On the n-type semiconductor side it allows only electrons to pass through it, while transport of holes (which are minority carriers) is due to recombination. Similarly p-type semiconductor side allows only holes to pass through it and transport of electron takes place by recombination.

Thus, three steps are involved in generating electricity from light: (i) absorption of photons, resulting in generation of electron–hole pairs, (ii) separation of carriers by the internal electric field created by p–n junction and collection at the electrodes resulting in potential difference and current in the external circuit, and (iii) potential difference at the electrodes of a p–n junction resulting in injection and recombination of carrier's which are the causes of losses [4,5].

Although the efficiency of solar cell is improving day by day, still there is a large gap between the theoretically predicted limit and the actual achieved efficiency. Improvement in the efficiency of solar cell even by few per cent makes a lot of difference in the watts per cent cost. Various factors, such as; spectral distribution, temperature and resistive load influence the electrical power output of solar cell and factors such as reflection, thermodynamics, charge carrier generation and conduction influence the conversion efficiency of a solar cell.

1.3. Parameters of a solar cell

Double diode model is used to define the parameters of the solar cell. The double diode model has the limitations that it gives erroneous results when applied to high efficiency solar cells. In actual devices the recombination becomes a complex function of carrier concentration, resulting in ideality factor and the saturation current varying with voltage. Still, for the sake of simplicity we have used the double diode mode to define the parameters. The equivalent circuit of solar cell is shown in Fig. 1 [6] and parameters of a solar cell are shown in Fig. 2 [7].

The current in the external circuit I can be written as, $I = I_L - I_D$, where I_L is the photocurrent and I_D is the diode (dark) current and

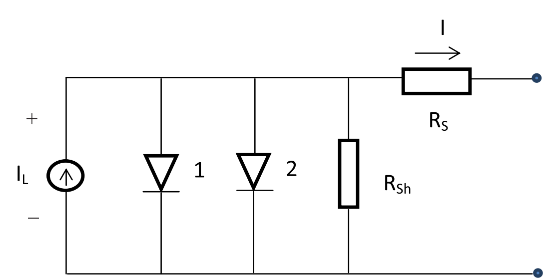

Fig. 1. Equivalent circuit of a solar cell.

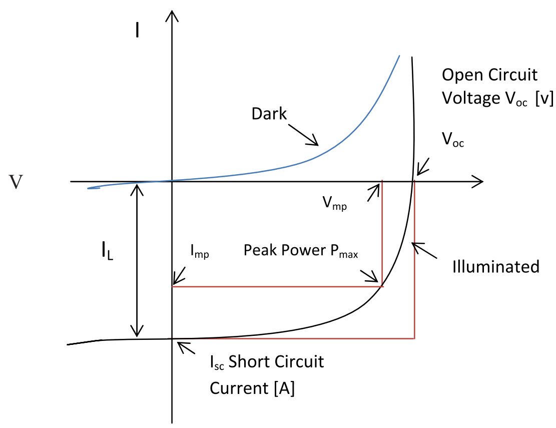

Fig. 2. *I–V* characteristics of a solar cell [7].

the total current, I_T is given as

$$I_T = I_0(e^{qv/kT} - 1) - I_L \tag{1}$$

where I_0 is the dark saturation current, the diode leakage current density in the absence of light; V is the applied voltage across the terminals of the diode; q is the absolute value of electron charge; k is Boltzmann's constant; and T is the absolute temperature (K).

For short circuit current ($V=0$)

$$I_{SC} = -I_L \tag{2}$$

For high value of $I_{SC,}$ there should be (i) minimum front surface reflection, (ii) minimum transmission losses and (iii) minimum surface and bulk recombination

For open circuit voltage ($I=0$)

$$V_{OC} = kt/q \ln(I_L/I_0 + 1) \tag{3}$$

Thus, for high value of V_{OC} (low value of I_0), there should be (i) high doping densities, (ii) low surface recombination velocities and (iii) large diffusion length.

Fill factor (FF) reflects the overall quality of solar cell [8].

$$FF = I_{MP}V_{MP}/I_{SC}V_{OC} \tag{4}$$

where $I_{MP}V_{MP}$ is the maximum power point.

For higher value of fill factor, series resistance should be low and shunt resistance should be high, which leads to less current dissipation as internal losses. Fill factor increases with the increase in the band gap of the semiconductor and for a good solar cell, its value should be greater than 80%.

The efficiency, η of a solar is ratio of generated electrical power (P_{max}) and incident light power (P_I)or

$$\eta = P_{max}/P_I \tag{5}$$

where

$$P_{max} = V_{MP}I_{MP} \tag{6}$$

1.4. Shockley–Quisser limit

Photons having energy less than the band gap are not absorbed while excess energy of photons having energy more than the band gap are wasted as heat. Thus, the quantum efficiency of a cell can be ~30% depending upon its band gap. Researchers are trying to achieve the efficiency higher than Shockley–Quisser limit by using various newly developed techniques. One of the methods is, including an intermediate band which absorbs excited electrons from valence band and allows its transition to conduction band. These bands allow two low energy photons to add up to one exciton and this is supposed to yield an efficiency of ~63% [9,10]. Another approach is impact or avalanche ionization. An electron with enough kinetic energy can knock a bound charge carrier from its bound state and make it free for conduction, thus creating an electron–hole pair. Thus, more than one pair per electron can be produced which shall lead to enhanced efficiency of a solar cell.

1.5. Different generations of solar cells

The solar cell can be categorized into four generations. First generation solar cells are based on p–n junction. They are made of c-Si (Si or Ge doped with phosphorous or boron). They are still dominating the marker share (about 80% of market share) as they are most efficient (about 22–24%). Because of having indirect band gap, its absorption coefficient in visible region is low and therefore a thicker absorber layer is required for achieving higher efficiency. Some light trapping techniques are used for increasing the efficiency. Second generation solar cells are based on thin films. Example includes amorphous Si, polycrystalline Si, CIGS, CdTe, CZTS, etc. Third generation solar cells are quantum dot based solar cells. Examples are multi-junction (other than Si), dye, organic, polymer etc. based solar cells. Fourth generation solar cells are based on hybrid-inorganic crystals within polymer molecules.

2. Requirements of photovoltaic materials

In order to be a suitable material for solar cell applications, materials should have certain characteristics which are summarized below.

2.1. Optical properties

2.1.1. Band gap

The band gap of material should be compatible with the available solar spectrum. If the band gap is too large, many photons possessing insufficient energy shall pass through the material without creating any electron–hole pair. But if the band gap is too small, many will have lot of excess energy which shall be dissipated as heat. Therefore, materials having only specific band energy are used. For efficient harvesting of solar energy band gap should be in range of 1–2 eV. Band gap dependence of conversion efficiency is shown in Fig. 3 [2]. Tandem structure can be used for utilizing the most part of the solar spectrum. In this structure, a material having higher band gap energy is deposited over the material having lower band gap. Thus, the first layer is transparent for low energy light photon and the bottom absorber layer with a low band gap can easily absorb the light unabsorbed by the first layer.

2.1.2. Absorption coefficient

The absorption coefficient of the material should be high, about 10^4–10^6 cm^{-1}. Materials with higher absorption coefficient can easily absorb photons and excite electrons into the conduction

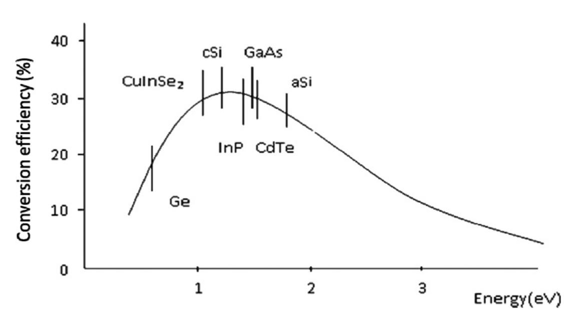

Fig. 3. Band gap dependence of conversion efficiency (AM 1.5, 300 K) [2].

band. For thin film solar cell, we need a thin absorption layer with good absorption coefficient. But, the absorption coefficient of Si layer is low in the visible region of solar radiation and therefore absorption layer should be more than 1 μm thick. Thus, the film deposition rate should be high in order to make solar cell commercially viable. For this purpose high power and very high plasma excitation frequency are used [6]. The optical absorption in indirect band gap semiconductor is lower than direct band gap semiconductor. The absorption coefficient can be enhanced at nanodimension [11].

2.1.3. Refractive index

For better optical properties, the refractive index of different layers in solar cell should be nearly equal. For example if a low refractive index layer is used in the middle of two high refractive index layer then it supports very high density of state and has more interaction with light and material.

2.2. Carrier concentration

Carrier concentration depends on the intensity of solar radiation falling on the surface of solar cell. When light falls on the solar cell, electron–hole pairs are generated and carrier concentration get enhanced, and if recombination takes place then carrier concentration decreases. Also, the concentration of dopant atom should be in a proper limit [12].

2.3. Transport properties

Transport properties are affected by drift and diffusion coefficients. If the electrons distribute themselves from the region of high concentration to low concentration, independent of electric field then it is called diffusion and if the external field causes the movement of electrons then it is called drift [12]. The drift and diffusion plays important role in solar cell.

3. Thin film solar cells

A brief discussion of thin film solar cell is presented below.

3.1. Advantages

A thin film solar cell has several advantages. Deposition of thin films of semiconductor is carried out using low cost methods (compared to Si processing). These results in savings in material and energy consumption and therefore the energy payback time are low. The cells can be made on flexible substrates and can therefore be integrated directly.

3.2. Basic requirements of thin film solar cell

For ideal solar cell, the main requirements of the material is that its band gap should be between 1.1 and 1.7 eV. The material should have direct band gap. It should produce good photoconversion efficiency. They should be stable (lifetime should be 20–30 years) and reliable [1]. The source material should be easily available, non-toxic, and cost-effective. It should not be hazardous to environmental. It should have good band offsets with respect to the window materials, there should not be interface state in the energy gap and carriers should be able to cross over the grain boundaries [13].

3.3. Different types of thin film solar cells

Various materials; like, amorphous Si (a-Si), copper indium gallium diselenide (CIGS), copper zinc tin sulphide (CZTS), cadmium Telluride (CdTe) and others are used for making thin film solar cell.

Amorphous Si (a-Si) solar cell has a band gap of ~1.6 eV and absorption length for the red and infrared solar photons exceed 1 μm and 100 μm, respectively [14,15]. The hole diffusion length for a-Si:H is 300–400 nm, which limits the solar cell absorber layer thickness to less than hole diffusion length [16]. As the thickness of absorber layer is limited to a few nanometres, it is difficult to use these photons for efficient carrier collection. This limits the efficiency of solar cell. Thus, enhancing the light absorption is essential for better result, which is done by different techniques including back reflector or light trapping configurations.

As discussed above, new materials; like, CIGS ($CuInGaSe_2$), CZTS (Cu_2ZnSnS_4), CdTe etc. are also used in thin film solar cell with good conversion efficiency. CIGS shows good stability over time and good resistance to ionized radiation and therefore may be suitable for space applications. The highest conversion efficiency of CIGS solar cell is 20.4% [17].

CIGS is a direct band gap material with band gap of 1.1–1.2 eV which is best suited for solar spectrum falling on earth; still there are some losses which limit the efficiency of CIGS solar cell or cause the power reduction. CIGS solar cell structure is shown in Fig. 4 [18]. These losses are optical and collection losses, recombination losses and resistance losses. CdTe is also used as an absorber layer with CdS as buffer layer and an efficiency of 18.7% has been reported by First solar [19]. But it has some problem such as toxicity of cadmium, scarcity of tellurium, cost etc. Another suitable material for thin film solar cell is CZTS, first synthesized and analysed in 1967 and has a band gap of ~1.45 eV [20]. CZTS is a quaternary compound semiconductor of $(I)_2(II)(IV)(VI)_4$ type with excellent PV effect and theoretical conversion efficiency as high as 32% is possible [21].

The cost of raw materials for CZTS PV technology is much lower than other three existing thin film PV technologies.

4. Losses in a solar cell

There are various losses which limit the performance of solar cells [22,23]. The different types of losses in a solar cell which reduce the efficiency of solar cell are described below.

4.1. Optical losses

Optical losses are due to non-absorption, thermalization, reflection, transmission and area loss.

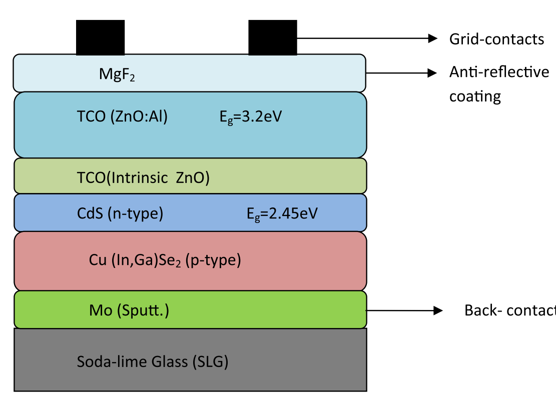

Fig. 4. Schematic structure of a $Cu(In,Ga)Se_2$-based solar cell [18].

4.1.1. Non-absorption

In single band gap solar cells, photons with energy lower than the band gap energy of the absorbing material are transmitted (Fig. 5). Thus, the energy of the photons having energy lower than the band gap energy is lost due to the non-absorption by the absorbing material. Thus, E_{Ph} (energy of incident photon) $< E_G$ (band gap energy) is not absorbed [24].

4.1.2. Thermalization

When $E_{Ph} > E_G$, thermalization occurs, it applies for photons which have energy higher than the band gap. The excess energy is dissipated as heat. This heat increases the temperature of solar cell which further increases the reverse saturation current due to increase in concentration of intrinsic carriers and diffusion length of minority carriers. This increase in reverse saturation current decreases the open circuit voltage [25].

The above two losses alone is responsible for loss of half of the incident solar energy in a solar cell.

4.1.3. Reflection loss

This occurs due to blocking of the light by top contact, reflection from the top surface and reflection from the back contact without proper absorption [5].

4.1.4. Transmission loss

This is due to the finite thickness of cell and the effect is enhanced in materials having low absorption coefficient.

4.1.5. Area loss

This loss is due to metal grid design or by metal electrode coverage [26].

These optical losses can be reduced by using an antireflective coating (ARC) of quarter wavelength thick on the top surface. The light wave reflected from the ARC is 180° out of phase with the light reflected from the top surface and when these two combine the resulting interference cancels the effect. Texturing of the top surface is done in such a way that light reflects in a proper manner and the reflection losses are less.

4.2. Collection losses

These losses are due to surface and bulk recombination at metal or semiconductor contact and recombination in depletion region. These recombination losses mainly affect the open circuit voltage. Impurities, crystalline defects and incomplete chemical bond on semiconductor acts as traps for photoexcited carriers, and recombination on these traps cause the reduction of photocurrent. The reduction in the concentration of impurities and defects can increase the diffusion length of minority carriers and this can decrease the recombination losses in a solar cell [12].

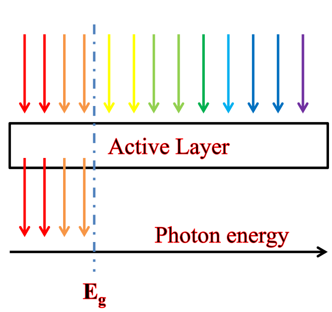

Fig. 5. Photons with energy lower than the band gap energy of the absorbing material are transmitted through the cell and consequently do not contribute to the useful electrical power output of the device.

Recombination losses can also be reduced by creating a heavily doped metallic region which acts as back contact, by chemical treatment of the materials or by using a thin layer of passivating oxides.

4.3. Resistance losses

Series resistance is due to the bulk resistance of semiconductor, bulk resistance of metal electrodes and due to the contact resistance between semiconductor and metal. Series resistance can be controlled by careful design of the top contact and emitter resistance [27]. Series resistance should be low for better efficiency of the solar cell because higher value of series resistance reduces the short circuit current. The shunt resistance is due to the leakage across the p–n junction, impurities and crystal defects. The value of shunt resistance should be low. This low value of shunt resistance causes reduction in open circuit voltage. Both series and shunt resistance losses decrease the efficiency and fill factor of the solar cell.

4.4. Metal/semiconductor contacts

Metal/semiconductor contacts on the front and back surface of a solar cell cause losses. The front contact is thin grid lines and back contact is a metallic coating. Reduction of resistance of the metal/semiconductor contact is one of the major means to decrease the power losses for cell [28].

These losses affect the efficiency of thin film solar cell; therefore it is necessary to reduce these losses in order to increase the efficiency of the solar cell. Various methods used for reducing these losses are discussed below.

5. Light trapping techniques

Different materials have different spectral range. For example, for crystalline Si (c-Si) solar cell, the spectral range is 600–1100 nm and for amorphous Si (a-Si), the spectral range is 600–800 nm. A large part of the long wavelength incident photons are not absorbed, which reduces the efficiency. Charge carriers generated far away from the p–n junction are also not effectively collected, owing to bulk recombination. To reduce these losses or to reduce the light induced degradation and minimize the process time, absorption layer thickness should be as low as possible. There are many techniques which are used for improving the efficiency of solar cell including various light trapping techniques. By using antireflection coating and nanotechnology based methods, efficiency can be enhanced. Various nanoparticles are used which scatter light in various modes or internally reflect light in multiple modes so that the optical path for absorption is much larger than the film thickness. Various light trapping techniques are discussed below.

5.1. Antireflection coating (ARC)

As discussed above, ARC is used to reduce the reflection from the front surface. This reduction is based on the destructive interference at the interface [29,30]. It consists of a layer of a dielectric material deposited on the surface of the active material of solar cell having a particular thickness. This layer should be transparent and is a quarter wavelength thick (thickness, $d = \lambda/4n$, where n is refractive index). The light wave reflected from the antireflection coating is 180° out of phase with the reflected wave from the semiconductor surface. This causes destructive interference, resulting in zero net reflected energy [31].

The refractive index of ARC should be between the materials on either side. Glass and Si have refractive index of 1.5 and 3.7 and for minimum reflection antireflection coating should have refractive index of ~2.4. Structure with ARC is shown in Fig. 6 [32,33].

Mostly, antireflective coatings are made of MgF_2 [34], Si_3N_4 and ITO are used. MgF_2 is a hard and durable coating, which reduces the reflection and increases the absorption. Similarly ITO is used to collect the carrier and act as ARC.

Salman et al. used ZnO/pores silicon (PS) layer as an antireflection coating in solar cells and the lowest effective reflectance was obtained for the ZnO/PS layers. These layers were an excellent ARC in enhancing and increasing the light conversion efficiency of solar cells (18.15%), which is close to the efficiency of the commercial solar cells with standard alkaline-textured pyramids and SiN_x single-ARC layer [35,36].

5.2. Surface texturing

This method is also used for reducing the reflection. This is done by making the surface rough or by etching the surface [5,37]. When light falls on textured surface, the chances of reflection gets reduced and it bounces back to the surface. Random and textured surfaces are more effective than flat surface and some particular textured geometry; like, inverted, pyramidal, upright and random textures is more effective [38]. All these geometrical textured surfaces are not suitable for all types of materials. These can be applied to some particular type of solar cell [39,40]. Generally, geometrical scale textures are less suitable for thin film solar cell because of low thickness of thin film solar cell. This result in smaller absorption i.e. large loss and also increases the minority carrier recombination. Textured surface on thin film solar cell is shown in Fig. 7 [41].

Pyramidal structures are suitable only for monocrystalline solar cell and these textured surfaces can also be suitable for strong absorbing materials. These reduce the thickness of solar cell and also reduce the bulk recombination and improve the photon absorption and increase the conversion efficiency [42–44]. On the textured surface, light is reflected in a proper fashion and this could increase the light path in the material up to $4n^2$ (where n is the index of refraction for the semiconductor) with textured interface on both sides of cell [45].

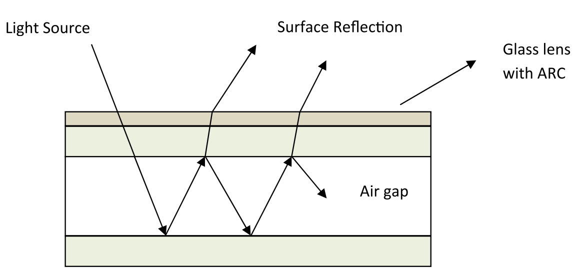

Fig. 6. Antireflection coating [32,33].

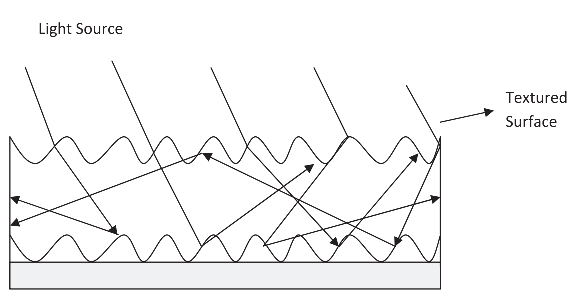

Fig. 7. Textured surface [41].

A 0.3% absolute efficiency boost was demonstrated using laser texturing on multicrystalline silicon compared to standard isotexture, with the laser-textured cells averaging just over 17% efficiency [46].

5.3. Back surface field (Bragg's reflector)

The main limitation of thin film solar cell is that the light photons do not stay trapped inside the solar cell for a long time when the thickness of absorber layer becomes less than the wavelength of light photons. In order to increase the optical path length of light photons, various light trapping techniques are used; such as, using a highly efficient reflector on the back of solar cell and texturing the back surface so that light photons reflect many times or stay trapped inside for a longer time. When radiation falls perpendicular to the device, optical path length is equal to the thickness of material and some photons may not get trapped. If light falls at some angle on the rear surface rather than perpendicular then optical path length increases and light gets totally reflected and stay trapped for a longer time and recombination of photons at back surface get reduced [5]. Fig. 8 shows the back surface field or grating pattern in Si thin film solar cell [47,48]. Mainly heavily doped Al and Ag particles are used for making back surface. In super substrate configuration metallic layer is deposited on a TCO interlayer at back surface which increases the reflection inside the cell by matching the refractive index [49,50]. But in the case of substrate configuration, a metallic film is deposited on the absorber layer [51]. The textured Bragg reflector surface was first deposited by using the lithographic method. Now, the low cost self-assembled approach is used.

A highly reflective surface is made by depositing a thin ZnO film on the metallic back surface through which light undergoes internal reflection. Metallic nanoparticles induced into the active layer are also used for light scattering and for enhancing the optical path length [52–56]. Blue light is absorbed in the solar cell while red light interacts with nanoparticles in guided mode and in surface plasmon polariton (SPP) mode [57–59]. Light in propagating waveguide mode is absorbed in semiconductor while carrier collection takes out of the plane. This causes reduction in thickness of TFSC due to improved carrier collection and reduced bulk recombination. According to Yablonovitch and Cody [45], the optical path length can be increased nearly 50 times by using Lambertain reflector. They also found that by using textured surface more carriers can be generated near the junction. The main requirement for this to happen is that the metal layer should be thicker than textured surface to ensure continuity.

Kuo et al. made a-Si:H thin-film solar cells with backside of TiO_2/SiO_2 which acted as distributed Bragg reflectors (DBRs) for applications involving building-integrated photovoltaics (BIPVs). Selectively transparent solar cells are formed by adjusting the positions of the DBR stop bands to allow the transmission of certain parts of light through the solar cells. Measurement and simulation results indicated that the transmission of blue light

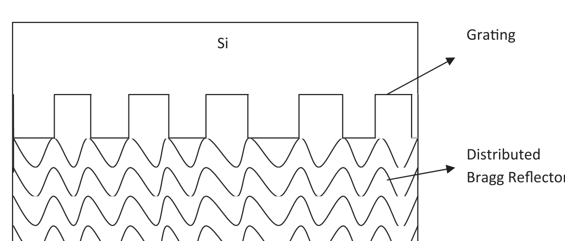

Fig. 8. Back surface field [47,48].

(430–500 nm) with the combination of three DBR mirrors has the highest increase in conversion efficiency [60].

5.4. Selective emitter structure

Selective emitter structure is mainly used in screen printing technology which has a great impact on recent development and is a very simple technology. This technology has a lightly doped emitter because if we heavily dope the top surface then the surface gets damaged. Selective emitter technology is younger technology and is widely used in screen printing. Selective emitter simply means heavy doping directly on metal with low contact resistance, which has problem over lightly doped emitter where the light penetrates [61,62]. Now, the rear surface passivation is also used to increase the efficiency with combination as AlO_x/SiN_x, SiO_2/SiN_x, and SiO_xN_y.

Phosphorus ink technology has been demonstrated as a simple and cheap method to realize selective emitter (SE) in crystalline silicon solar cells through mass production by a professional photovoltaic company. It has achieved average conversion efficiency (η) of 19.01% with peak η of 19.27% for the SE solar cells based on commercial-grade p-type silicon substrate, which is much higher than that of the homogeneous emitter counter parts whose average η is 18.56% [63].

5.5. Surface passivation

This technique is used to reduce the recombination at both front and back surfaces which occurs due to discontinuity at various interfaces or due to dangling bond and impurities present in the solar cell. These impurities or dangling bond act as recombination centre and reduce the efficiency [64]. To reduce recombination, surface passivation is used which passivates the surface by using a dielectric surface such as Si, SiO_2, Si_3N_4. Surface passivation can also be carried out by chemical treatment or by using a thin layer of passivizing oxide. Surface passivate can also be done by heavily doping the low doped semiconductor [65].

Surface passivation technique was successfully applied in the solar cell to enhance the efficiency [66].

5.6. Absorber material thickness

The thickness of absorber material has a profound effect on the efficiency of solar cell. The excess energy of the photons having energy higher than the band gap energy and energy of the photon having energy lower than the band gap energy are wasted which causes loss of radiation. This happens due to the insufficient thickness of absorber materials which depends on absorption coefficient of materials and wavelength of absorbed photon [24,67]. Low energy photons have low absorption coefficient and high energy photons have high absorption coefficient. For maximum absorption of radiation absorption coefficient should be nearly equal to the absorption length or photon wavelength. Thus thickness of absorber material for zero transmission loss, d is given as

$$d = \frac{1}{\propto (Eg)} \tag{7}$$

where $\propto (Eg)$ is the absorption coefficient of photon of energy Eg.

5.7. Resonant dielectric structure

Resonant dielectric structure is placed on the top of solar cell [36]. This structure can super sum very confined mode/resonant mode that can leak into the active material. Mainly dielectric nanospheres are used which is relatively insensitive to angle of incident [68]. The material used in this sphere is lossless and inexpensive made of silica and absorbing surface remains perfectly flat which is unadvantageous towards some material that have good electrical properties and we can expect 10% enhancement compared to solar cell which already has antireflection coating. Solar cell with resonant dielectric structure is shown in Fig. 9 [69,70].

5.8. Structure

Back contact is Ag and absorbing layer is of AlZnO is used in order to prevent diffusion of Ag in case of a-Si. Then the active layer is of Si and a transparent coating is of ITO which is used to collect the carrier and act as antireflection coating. The description of structure is given in Fig. 10 [71]. This is the resonant dielectric structure to increase the efficiency of solar cell.

At shorter wavelength hemispherical dielectric nanomaterial scatter light more efficiently than spherical particles.

The difference between the thermodynamic limit of photovoltaic conversion and the limit of efficiency of traditional bulk semiconductor solar cells can be gradually bridged if an optimum energy band structure is achieved, SiO nanosphere and honey comb structure have been used for enhancing the solar cell efficiency [72–74].

5.9. Metallic nanoparticles (plasmonic effect)

Nanotechnology plays an important role in enhancing the efficiency of solar cell. Si is poor in absorbing infrared light and thus most of solar light is wasted and thus increased thickness of the material is required. To reduce this problem or to decrease the thickness of thin film solar cell, metallic nanoparticles are used on the top of active layer which have the strong ability to scatter the incident light. This is also called plasmonic effect. Mainly Ag nanoparticles are used in enhancing the efficiency of TFSC. The nanoparticles behave like small mirror; concentrate light more strongly than normal mirrors. This effect is based on surface

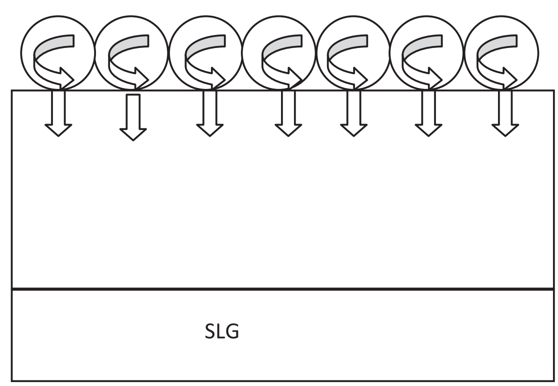

Fig. 9. Resonant dielectric sphere [69,70].

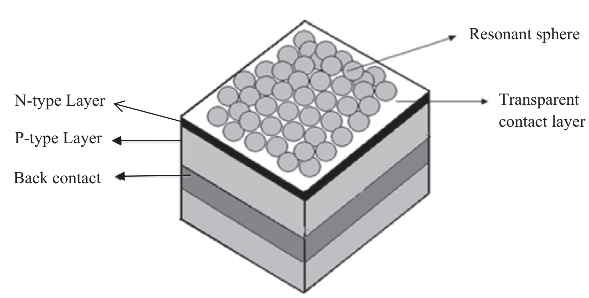

Fig. 10. Description of structure [71].

plasmon, the collective motion of electrons [36,75–77]. Nanoparticles have a particular frequency called resonant frequency at which incident light will strongly excite the collective oscillation of electrons [78,79]. This causes strong absorption or strong scattering of light. When light falls on the surface of solar cell it is scattered in different directions. These nanoparticles preferentially scatter light into high index material leading to enhance coupling with underlying semiconductor and thus reduces reflectance over a broad spectral range. In nanoparticles, scattering is stronger. Fig. 11 describe the scattering from metal nano-particles at the surface of solar cell [54,57].

Light generated electrons and holes travel over a much shorter path; this greatly reduces the recombination losses. Thus, the solar cell can be very thin, ~100–150 nm. Metallic nanoparticles act as nanoantennas to couple the plasmonic near field to semiconductor, and thus increasing the effective absorption. Surface plasmon could be excited by grapheme type structure as well. Excitation of localized surface plasmon in metal nanoparticles embedded in semiconductor is shown in Fig. 12 [78].

The energy band gap of various layers can be adjusted to the desired value by varying the size of nanoparticles [54]. This provides more design flexibility in absorber and window layer of solar cell. Using nanomaterials, efficiency can also be enhanced by varying the size of the nanomaterials; which further changes the light absorption. By changing the size of plasmonic materials, one can overlap the absorption and scattering spectrum of these materials [9,80]. Metal nanoparticles are being used to achieve 33% enhancement in photocurrent of thin Si solar cell. Nanowires of GaAs can concentrate sunlight up to 15 times more. This affects the efficiency greatly [81].

5.10. Fishnet structure for a-Si:H thin film solar cell

In plasmonic solar cell passivation layer is used at both; front and back end to reduce the recombination losses [82]. This passivation layer is mostly flat but other metal nanoparticles having different shapes; like, spheres, hemispheres, disks, spheroids and pyramidal are also used [83] The resonance frequency for these metal particles is less than $\lambda/10$ in size, is always lower than 500 nm [84]. Particles may block the incident light if they are bigger because in that case the resonance becomes weaker. In light trapping methods various planer structures such as grating and

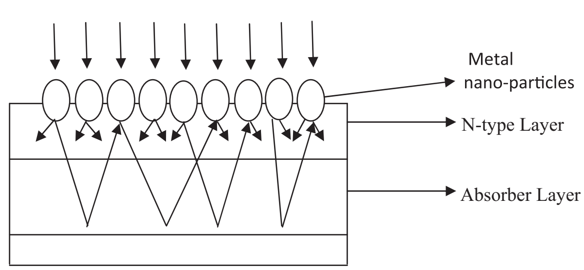

Fig. 11. Scattering from metal nanoparticles at the surface of solar cell [54,57].

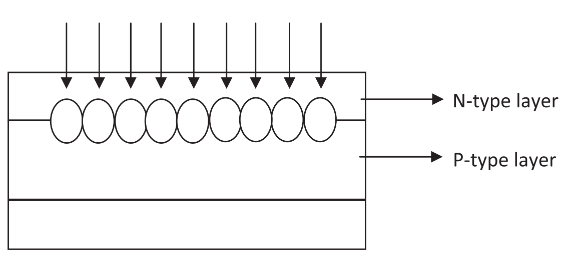

Fig. 12. Excitation of localized surface plasmon in metal nanoparticles embedded in semiconductor [78].

photonic crystals have been proposed to enhance the solar cell efficiency and structure like fishnet metastructure is used for increasing the light absorption in thin film a-Si:H solar cell [85–88]. Complete structure; size, layout and orientation are very important parameters in determining the resonance [89–91]. In fishnet structure, a comparable impedance of both material and fishnet metastructure is required, which takes place at a particular resonance frequency of 681 nm and is highly flexible because this can be controlled by metal structure. This impedance matching is required for low reflection and high absorption. Therefore, light absorption enhances at resonance frequency and provides higher conversion efficiency.

5.11. Electron reflector

The record efficiency of CdTe solar cell is 16.5% while theoretical efficiency is 29% and this is recorded at open circuit voltage of 0.845 V, which gives efficiency lower than the expected at band gap of 1.5 eV. Most of incident solar light is absorbed at ~600 nm and has large optical absorption [92]. To increase the open circuit voltage and conversion efficiency one has to increase charge carrier density and lifetime and electron reflector is used at the back contact of cell in order to accomplish this [93]. The electron reflector method is more practical and less costly. Under forward biased condition electron reflector will reflect minority carrier electrons and thus reduce the back surface recombination. Electron reflector can be formed by adding a layer of p-type material with large band gap at back surface of CdTe absorber. Mostly CdZnTe and CdMgTe are used as ER [94].

6. Other parameters affecting the efficiency of solar cell

The efficiency of solar cells can also be improved using some other techniques:

Solar tracker: The maximum power point of a photovoltaic material varies with incident illumination. For large systems where the extra expense can be justified, a maximum power point tracker can be used, which can track the instantaneous power by continually measuring the voltage and current (and hence, power transfer), and uses the information to dynamically adjust the load in such a way that the maximum power is always transferred, regardless of the variation in lighting. In other words, the ability of a panel to “track” the sun means its ability to maintain the solar radiation at a perpendicular angle. Essentially, it is desired that the panels points toward the sun.

Solar concentrator: One of the ways to “boost” the solar power is by using solar concentrator. By increasing the light intensity, the number of photogenerated carriers increases, resulting in increase in efficiency up to 15% [95]. The “concentrator systems” have begun to become cost-competitive as a result of the development of high efficiency GaAs cells. A typical concentrator system may use a light intensity of 6–400 times the sun, and increase the efficiency of a one sun GaAs cell from 31% to 35% at AM-1.5.

Transparent conducting oxides (*TCO*): TCO have wide band gap between 3 and 4 eV and would not be expected to have significant intrinsic conductivity. They can be extrinsically doped with cation from one group higher in periodic table (Al in ZnO). Intrinsic O_2 vacancies are believed to contribute to carrier concentration. In extrinsically doped TCO's not all the impurities are ionized i.e. extrinsically active. They often depend on fabrication condition. TCO layer act as ARC due to change of refractive indices of interface. A metallic layer is deposited onto the TCO interlayer which acts as back contact

surface. This back contact surface improves the refractive indices [96].

In CIGS and CdTe technologies, nanostructured aluminium zinc oxide layer is used as TCO and is deposited on the top of the absorber and intermediate layer by magnetron sputtering. But in case of a-Si, nanostructured AlZnO is used as the reflective layer on lower substrate or as TCO on top layer. The nanostructured AlZnO has high transparency to visible and near infrared solar spectrum and low electrical resistivity. This also provides textured surface geometry, which enhances the reflection and has high chemical stability and provide better efficiency [97].

7. Conclusions

Through this review, an effort has been made to describe the physical principles which limit the performance of solar cell. Various light trapping techniques, techniques to reduce the reflection of light from surface, methods to reduce the recombination, optimization of absorber material thickness, use of surface plasmon resonance, and other techniques like solar tracker and solar concentrators have been discussed. By understanding these factors and its origin, efforts can be made to enhance the efficiency of thin film solar cell.

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